



Health Management Considerations for Electrified Aircraft Propulsion Systems

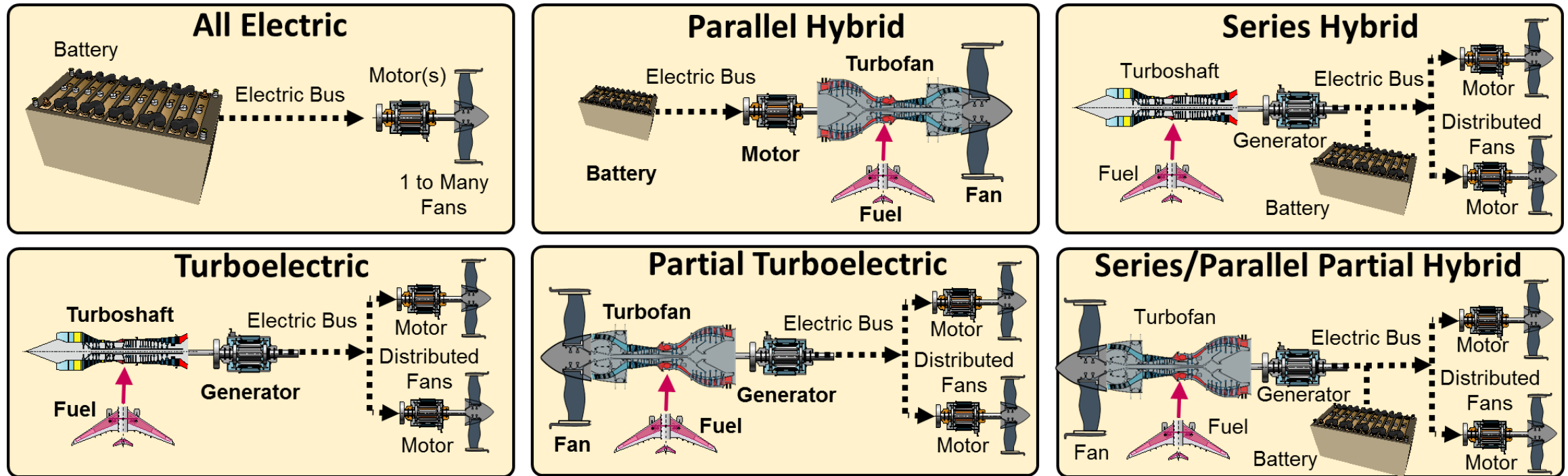
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SAE E32 Aerospace Propulsion Health Management Committee Meeting
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Hybrid meeting (in-person Madrid, Spain and virtual)

Electrified Aircraft Propulsion (EAP)

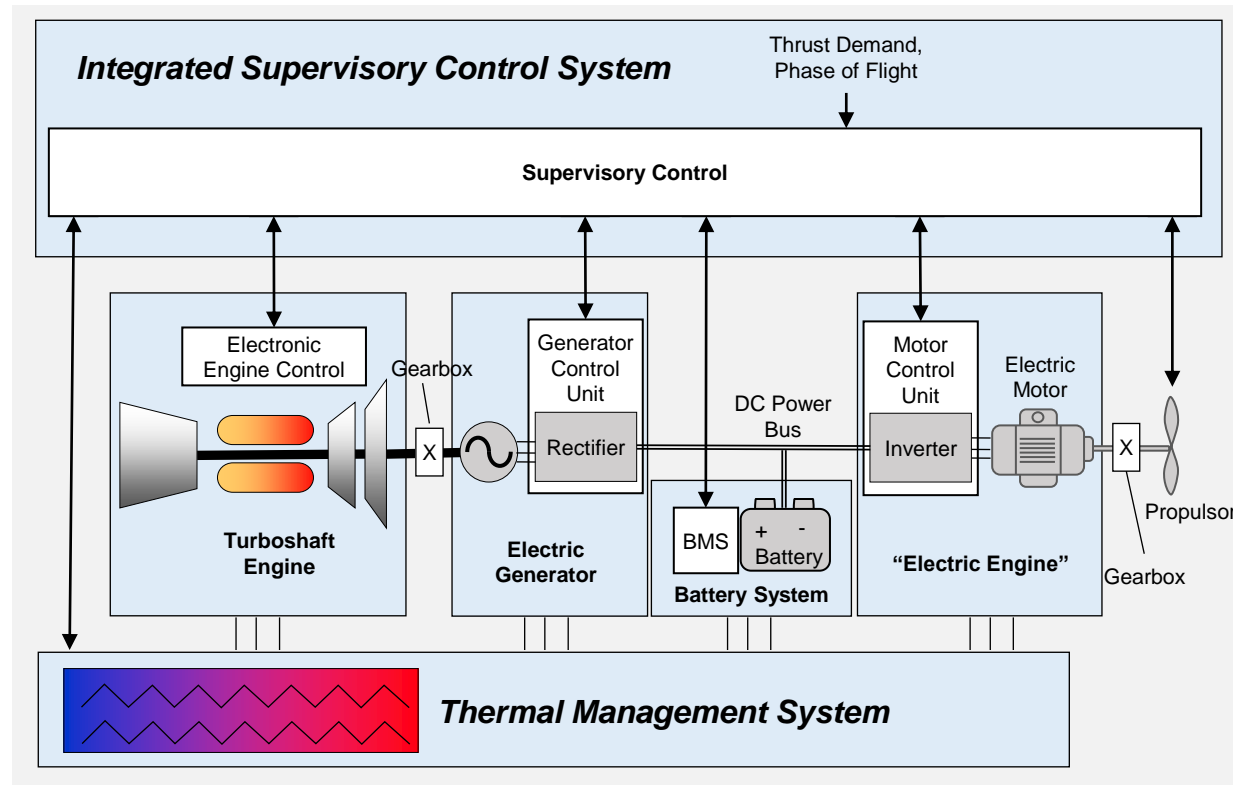


- Electrified Aircraft Propulsion relies on the generation, storage, and transmission of electrical power for aircraft propulsion



EAP Architecture Options

Overview of EAP System Components



Generic Hybrid Electric Propulsion System

EAP System Components

- **Supervisory Control:** Interface between vehicle and propulsion system.
- **Gas Turbine Engines:** Turbomachinery that converts fuel into thrust and mechanical power.
- **Gearboxes and Mechanical Drives:** Used for transferring mechanical power throughout EAP system.
- **Electric Machines:** Generators and motors. Used for converting mechanical power into electricity or vice versa.
- **Power Electronics and Power Distribution Systems:** Handles switching, power conversion, and transmission of electrical power throughout system.
- **Energy Storage Systems:** Systems for the storage of electrical energy such as batteries and supercapacitors.
- **Propulsors:** Motor driven propellers or fans used to generate thrust.
- **Thermal Management Systems:** Provide system cooling and heat dissipation

EAP Subsystem Degradation, Faults, Failure Modes, and Effects

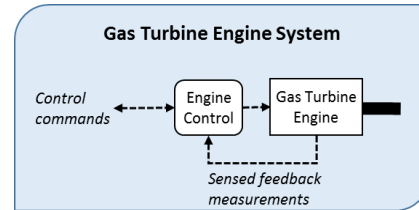


- EAP degradation, faults, and failure modes present new health management challenges ...
- Requires background understanding of:
 - Electrical engineering
 - Electrical system control and concept of operations (motor control, generator control, battery management systems)
- Requires new sensor measurement types
 - Current, voltage
- Electrical systems don't always degrade/fail gracefully
 - Makes early (timely) diagnosis to enable maintenance challenging

EAP Subsystem Degradation, Faults, Failure Modes, and Effects (cont.)

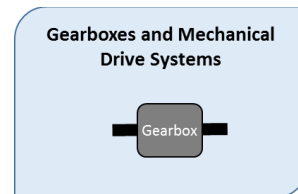


Gas Turbine Engines



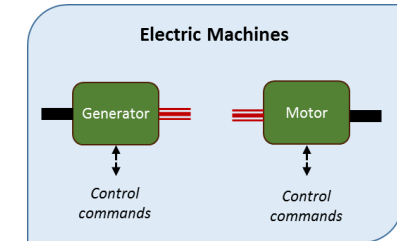
<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none"> • Blade erosion/fouling • Sensor faults • Actuator faults • Blade failure • Engine shutdown (various causes) • Partial power loss (various causes) • Loss of speed control (various causes) 	<ul style="list-style-type: none"> • Engine performance reduction • High vibration • Elevated temperatures • Complete/partial loss of engine power

Gearbox, Transmission, Mechanical Drives

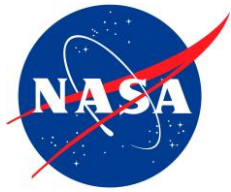


<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none"> • Bearing spalling, failure • Gear/Gearbox misalignment, failure • Offtake/drive shaft failure • Loss of drive/gearbox oil pump • Loss of drive/gearbox oil cooler • Oil leaks 	<ul style="list-style-type: none"> • High vibration • Elevated temperatures • Complete or partial loss of engine mechanical power offtake and ability to drive electric generators or propulsors

Electric Machines (Motors, Generators)

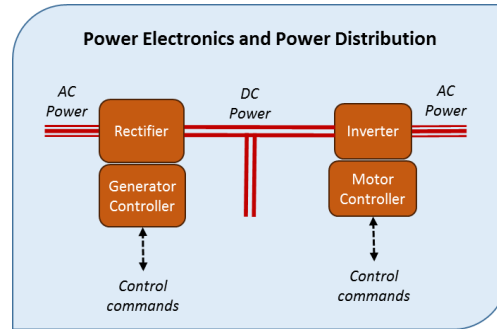


<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none"> • Shaft failure • Bearing failure • Stator winding failure (short circuit, open circuit) • Insulation failure • Rotor mass unbalance • Broken rotor bar • Air gap eccentricity • Loss of cooling • Overheating/fire • Power supply-related electrical fault (voltage or current levels, phasing) 	<ul style="list-style-type: none"> • High vibration • Elevated temperatures • Phase loss • Partial power loss • Complete loss of power



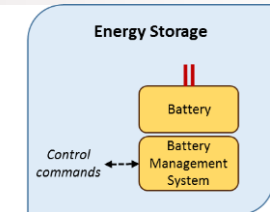
EAP Subsystem Degradation, Faults, Failure Modes, and Effects (cont.)

Power Electronics and Power Distribution Systems



<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none">• Potential Power Electronics Faults/Failures<ul style="list-style-type: none">○ AC supply-line failure (open-circuit, short-circuit, phase-to-phase short, etc.)○ Diode failure○ Link capacitor failure○ Transformer failure○ DC supply voltage failure○ Transistor failure○ Motor terminal supply line failure○ Loss of cooling○ Controller failures○ Loss of motor speed control• Potential Electric Bus Faults/Failures<ul style="list-style-type: none">○ Short circuit○ Open circuit○ Corona discharge○ Arcing○ High EMI	<ul style="list-style-type: none">• Voltage sag, high current levels• Degraded power quality (voltage ripple, power instabilities)• Low power• Complete loss of power

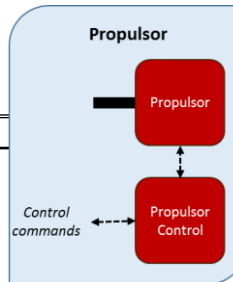
Energy Storage (Battery)



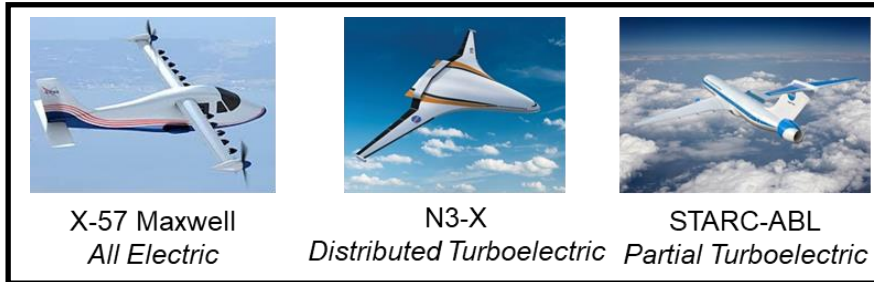
<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none">• Internal shorts• Thermal runaway / fire• Aging and internal mechanical stress (anode, cathode, separator), energy density degradation• Depleted state of charge (various faults)• Battery management system faults• External short/open circuit	<ul style="list-style-type: none">• Reduction in energy storage capacity• Reduction in discharge/charge rate• Complete loss of functionality

Propulsors

<i>Fault/Failure Modes</i>	<i>Effects</i>
<ul style="list-style-type: none">• Seizure• Shaft failure• Bearing failure• Blade damage/failure• Foreign object damage (FOD)• Environmental particulate fouling• Loss of control functionality (variable nozzles, pitch, etc.)	<ul style="list-style-type: none">• Loss of propulsor thrust• Reduction in propulsor thrust• Loss of propulsor pitch control



Extending Gas Path Analysis to Electrified Aircraft Propulsion Systems



Example NASA EAP Concept Vehicles

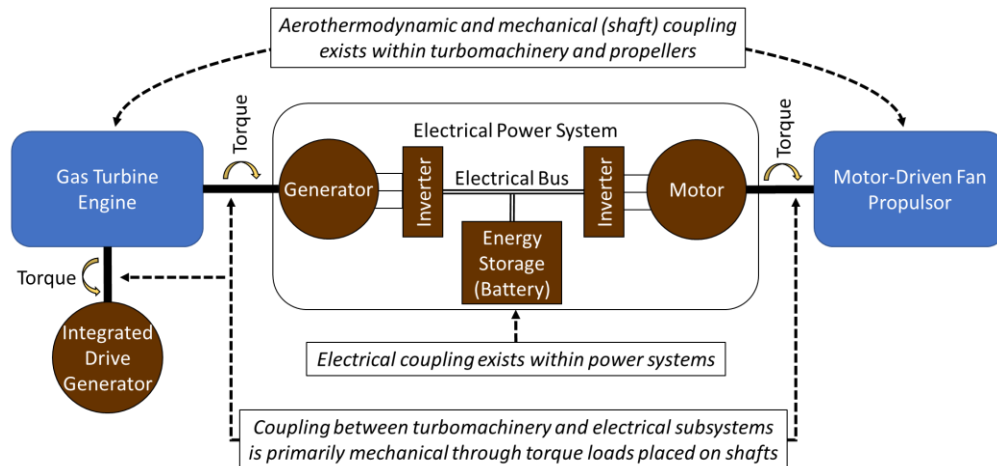
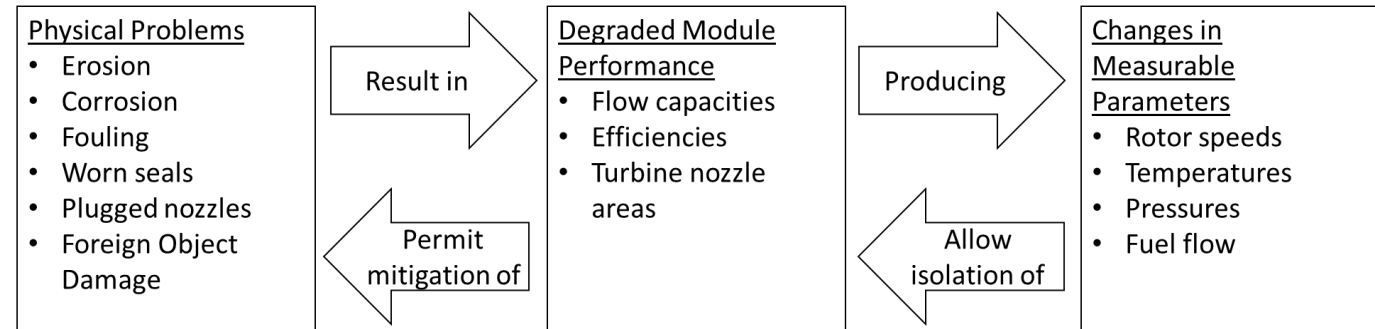


Illustration of Subsystem-to-Subsystem Coupling in a Notional EAP System



Gas Path Analysis Process

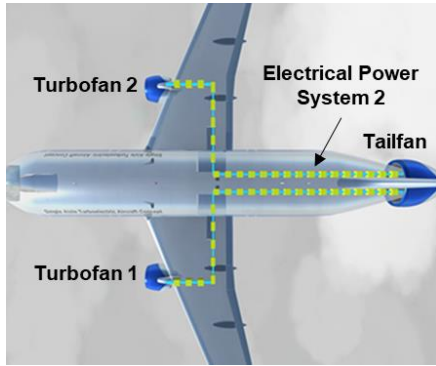
- Leverages analytical knowledge of coupling (parameter interrelationships) inherent in the gas turbine cycle

Question: Can conventional gas path analysis techniques be applied to electrified aircraft propulsion systems?

Example Application of Gas Path Analysis to STARC-ABL NASA EAP Concept Aircraft



Reference: Simon, D.L., Thomas, R., Dunlap, K.M., "Considerations for the Extension of Gas Path Analysis to Electrified Aircraft Propulsion Systems," ASME GT2021-58578, 2021 ASME Turbo Expo, June 7-11, Virtual, Online <https://doi.org/10.1115/GT2021-58578>



NASA STARC-ABL

Influence coefficient matrix H

Health parameters x

Measurements z

Measurement noise v

$$z = Hx + v$$

Measurement Equation

$$\hat{x} = (P_x^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1} z$$

Estimation Equation

Key Findings

- Demonstrated successful application of a conventional gas path analysis performance estimation approach to an electrified aircraft propulsion architecture
- A partitioned approach towards the estimation problem setup can be applied enabling health parameter estimates at the subsystem level
 - Measured or inferred level of torque applied to mechanical shafts that couple subsystems is key
- Presented approach and equations are generic and applicable to any electrified aircraft propulsion architecture of an interconnected nature

STARC-ABL Influence Coefficient Matrix, H (27 x 30)

Sensors		Health Parameters																													
		Turbofan 1										Turbofan 2										Power System 1					Power System 2				
		η_{fan}	η_{fan}	η_{LPC}	η_{LPC}	η_{HPC}	η_{HPC}	η_{HPT}	η_{HPT}	η_{LPT}	η_{LPT}	η_{fan}	η_{fan}	η_{LPC}	η_{LPC}	η_{HPC}	η_{HPC}	η_{HPT}	η_{HPT}	η_{LPT}	η_{LPT}	η_{gen}	η_{rec}	η_{bat}	η_{bat}	η_{gen}	η_{rec}	η_{bat}	η_{bat}	η_{fan}	η_{fan}
		η_{fan}	η_{fan}	η_{LPC}	η_{LPC}	η_{HPC}	η_{HPC}	η_{HPT}	η_{HPT}	η_{LPT}	η_{LPT}	η_{fan}	η_{fan}	η_{LPC}	η_{LPC}	η_{HPC}	η_{HPC}	η_{HPT}	η_{HPT}	η_{LPT}	η_{LPT}	η_{gen}	η_{rec}	η_{bat}	η_{bat}	η_{gen}	η_{rec}	η_{bat}	η_{bat}	η_{fan}	η_{fan}
Turbofan 1	N ₃	0.313	-0.282	-0.274	-0.142	-0.399	0.491	-0.297	0.671	0.591	-0.472	0	0	0	0	0	0	0	0	0	0	-0.156	-0.156	-0.157	-0.157	0	0	0	0	0.260	-0.159
	P ₁₃	0.311	-0.010	-0.016	0.000	-0.001	-0.002	0.001	-0.003	-0.003	0.002	0	0	0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0	0	0	-0.001	0.001
	P ₂₅	-0.106	0.364	1.401	-0.149	-0.501	-0.924	0.355	-1.358	-1.153	0.792	0	0	0	0	0	0	0	0	0	0	0.205	0.205	0.206	0.206	0	0	0	0	-0.342	0.209
	T ₂₅	0.000	0.008	0.233	-0.310	-0.096	-0.173	0.068	-0.237	-0.207	0.150	0	0	0	0	0	0	0	0	0	0	0.040	0.040	0.040	0.040	0	0	0	0	-0.066	0.040
	P ₃₃	0.568	-0.267	0.465	-0.098	-0.029	0.039	-1.190	0.159	0.274	-0.618	0	0	0	0	0	0	0	0	0	0	-0.184	-0.184	-0.185	-0.185	0	0	0	0	0.306	-0.188
	T ₃	0.325	-0.293	-0.212	-0.268	-0.146	-0.143	-0.473	0.541	0.500	-0.477	0	0	0	0	0	0	0	0	0	0	-0.149	-0.149	-0.149	-0.149	0	0	0	0	0.247	-0.151
	T ₄₈	0.534	-0.508	-0.598	-0.232	-0.125	-0.225	0.088	-0.311	0.034	-0.928	0	0	0	0	0	0	0	0	0	0	-0.281	-0.281	-0.282	-0.282	0	0	0	0	0.467	-0.287
Turbofan 2	W ₁	1.100	-0.786	-0.247	-0.232	-0.101	-0.181	0.066	-0.242	0.266	-1.612	0	0	0	0	0	0	0	0	0	0	-0.483	-0.483	-0.483	-0.483	0	0	0	0	0.800	-0.492
	N ₃	0	0	0	0	0	0	0	0	0	0	0.313	-0.282	-0.274	-0.142	-0.399	0.491	-0.297	0.671	0.591	-0.472	0	0	0	0	-0.156	-0.156	-0.157	-0.157	0.260	-0.159
	P ₁₃	0	0	0	0	0	0	0	0	0	0	0.311	-0.010	-0.016	0.000	-0.001	-0.002	0.001	-0.003	-0.003	0.002	0	0	0	0	0.000	0.000	0.000	0.000	-0.001	0.001
	P ₂₅	0	0	0	0	0	0	0	0	0	0	-0.106	0.364	1.401	-0.149	-0.501	-0.924	0.355	-1.358	-1.153	0.792	0	0	0	0	0.205	0.205	0.206	0.206	-0.342	0.209
	T ₂₅	0	0	0	0	0	0	0	0	0	0	0.000	0.008	0.233	-0.310	-0.096	-0.173	0.068	-0.237	-0.207	0.150	0	0	0	0	0.040	0.040	0.040	0.040	-0.066	0.040
	P ₃₃	0	0	0	0	0	0	0	0	0	0	0.568	-0.267	0.465	-0.098	-0.029	0.039	-1.190	0.159	0.274	-0.618	0	0	0	0	-0.184	-0.184	-0.185	-0.185	0.306	-0.188
	T ₃	0	0	0	0	0	0	0	0	0	0	0.325	-0.293	-0.212	-0.268	-0.146	-0.143	-0.473	0.541	0.500	-0.477	0	0	0	0	-0.149	-0.149	-0.149	-0.149	0.247	-0.151
Power System 1	T ₄₈	0	0	0	0	0	0	0	0	0	0	0.534	-0.508	-0.598	-0.232	-0.125	-0.225	0.088	-0.311	0.034	-0.928	0	0	0	0	-0.281	-0.281	-0.282	-0.282	0.467	-0.287
	W ₁	0	0	0	0	0	0	0	0	0	0	1.100	-0.786	-0.247	-0.232	-0.101	-0.181	0.066	-0.242	0.266	-1.612	0	0	0	0	-0.483	-0.483	-0.483	-0.483	0.800	-0.492
	Q _{urb}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.001	-1.001	-1.003	-1.003	0	0	0	0	1.661	-1.020
	I _{gen}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	-1.001	-1.003	-1.003	0	0	0	0	1.661	-1.020
	I _{bat}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0.000	-1.003	-1.003	0	0	0	0	1.661	-1.020
Power System 2	I _{bat}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0.000	0.000	-1.001	0	0	0	0	1.657	-1.018
	I _{rec}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I _{bat}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I _{rec}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I _{bat}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tailfan	Q _{urb}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P ₅	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T ₅	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

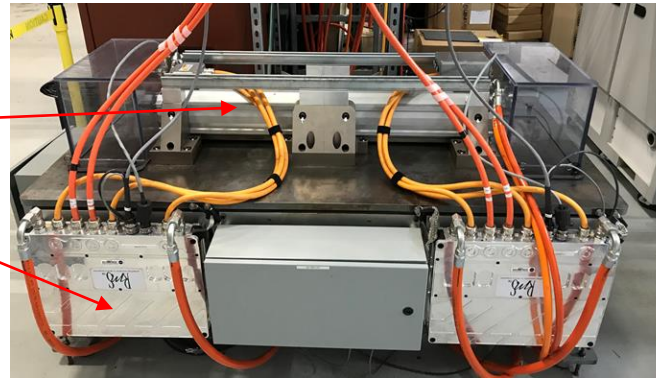
Legend

Turbofan Influence Coefficients	Power System Influence Coefficients	Tailfan Influence Coefficients	Inter-Subsystem Influence Coefficients
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Electric Machine Voltage and Current Measurement Information



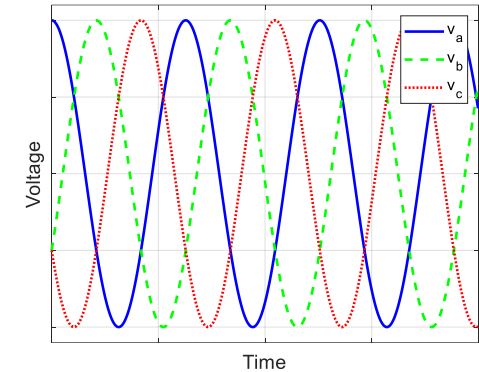
- 3-phase alternating current (AC) motors and generators
- Power converters include inverters (DC to AC) and rectifiers (AC to DC)
- 3-phase voltage and current dynamics in the ~kHz's range
- Direct-quadrature-zero (dq0) transformation is commonly applied to simplify analysis
- Analogous to accelerometer FFT- greatly reduces data transfer and archival requirements



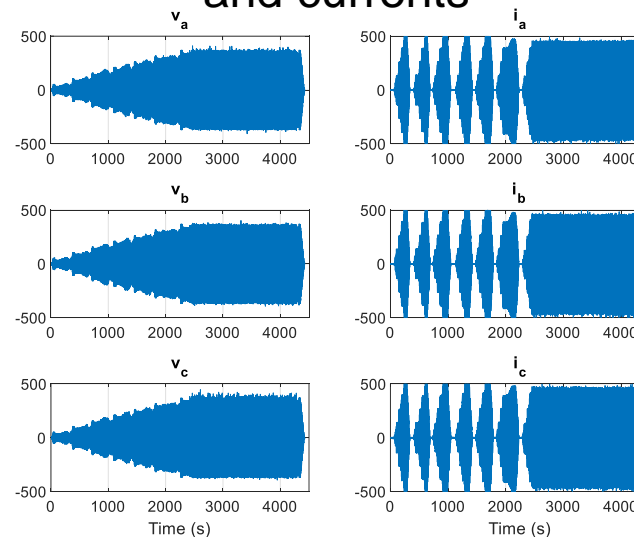
$$v_a = V_m \cos(\omega_t)$$

$$v_b = V_m \cos\left(\omega_t - \frac{2\pi}{3}\right)$$

$$v_c = V_m \cos\left(\omega_t + \frac{2\pi}{3}\right)$$



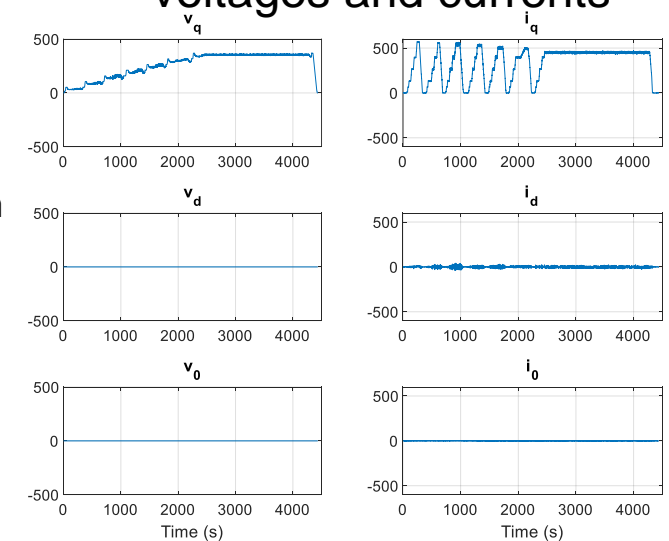
3-phase voltages
and currents



dq0
transform



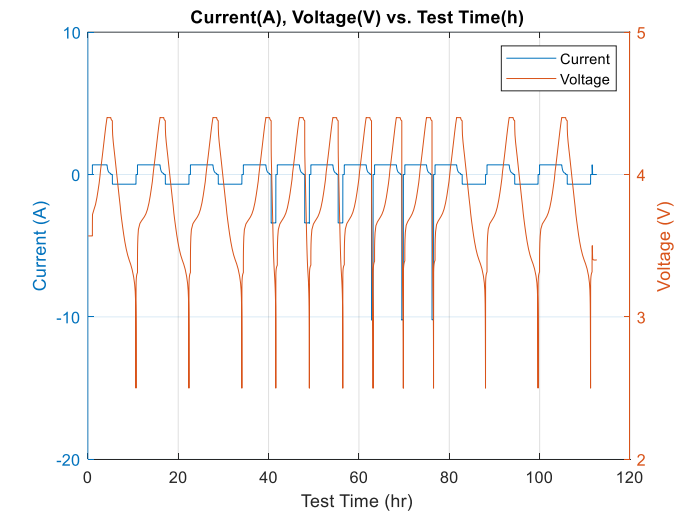
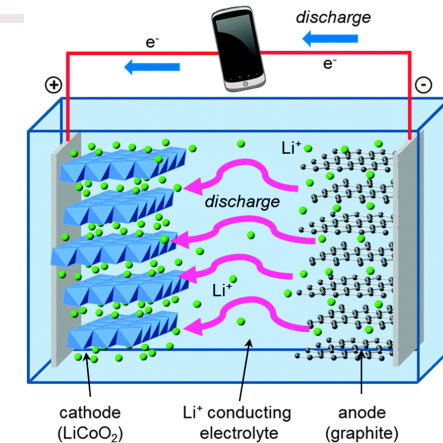
dq0 reference frame
voltages and currents



Battery Health Management (HM)



- Battery Aging Mechanisms
 - Decrease in mobile Li ions
 - Increase in internal resistance
 - Potential dendrite growth (thermal runaway risk)
- Battery Fault Diagnostics and Prognostics Goals
 - State of charge (SoC) estimation
 - End of discharge (EOD) prediction
 - End of Life (EOL) prediction
 - See: <https://ti.arc.nasa.gov/tech/dash/groups/pcoe/battery-prognostics/>
- Health Management Con-ops Considerations
 - All-electric designs require post-flight ground-based battery recharge (provides a more repeatable and controlled HM opportunity)
 - Hybrid designs enable battery discharge and recharge in-flight (adds greater variability and poses a more challenging HM problem)
- SAE AE-7D and HM-1 Committees discussing the creation of Li-Ion battery HM document



Battery discharge/charge cycle testing

Electrified Aircraft Propulsion HM Summary ...



- Many conventional subsystems remain in EAP architectures – e.g., gas turbines, rotating drives, gearboxes, propellers/fans, etc.
- But new challenges must be addressed ...
 - Architectures are more coupled and integrated in nature
 - Boundary between propulsion system and vehicle not as clearly defined
 - Might require means of partitioning the health management problem by subsystem
 - Data compression and feature extraction techniques for high-frequency electrical system measurements will be necessary
 - Electrical systems may not exhibit graceful degradation / failure making timely diagnostics and prognostics more challenging